SCOPE 27 - Climate Impact Assessment

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5 Agriculture

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5.1 INTRODUCTION

Not a single farmer, forester or stockbreeder needs any reminder that production systems are subject to the vagaries of climatic variation and the hazard of extreme weather events. The primary role of climate and weather in conditioning biological and physical processes and in determining much of the structure and function of both natural and man-modified systems should need no further emphasis. Yet, the development, testing and practical application of methods of agroclimatic analysis have not been given a high priority in most agricultural and biological research programs. Why is this so?

While there are intrinsic problems, the major limitations have been extrinsic. Farm, forest and grazing management involve a mix of controlled and uncontrolled variables. Since climate and weather are, for most practical purposes, uncontrolled, research emphasis has been given to those components of the production system that can be subject to some measure of control. Thus, for the past century of active development, agricultural research has been pedocentric and genocentric, that is, major effort has been devoted to soil description, classification and amelioration, and genetic improvement of crops and livestock. Since World War II increasing effort has been devoted to chemical and biological control of pests and pathogens.

In addition, the prevailing strategy of agricultural research and development is based on extensive networks of experimental sites at `representative' locations, with transfer of results by analogy to `similar' sites. Thus, for any experiment at such a site the climate and weather are taken as given, i.e., as a common component of all treatments. Such a framework is not conducive to the development of a general understanding of crop/environment interactions.

Intrinsic limitations to the development of methods of agroclimatic analysis have been that:

1. basic understanding of physical and biological processes involved in crop/climate and crop/weather interactions is limited (though now developing rapidly);
2. available modes of analysis lack generality and tend to be descriptive, rather than prescriptive; static rather than dynamic;

3. the necessary climatic data are inadequate, unavailable, or non-existent; and
4. matching sets of crop/soil/weather-management data for widely contrasting environments and production systems are not available.

New approaches and data now becoming available may remove most of these limitations. Even so, the future of agroclimatic analysis and synthesis hinges on convincing demonstrations of their utility, at scales ranging from local to global.

In order to place the more traditional and the newly developing methods of analysis and synthesis in perspective I have used a framework developed elsewhere (Nix, 1968, 1980, 1981). Progress toward an ultimate goal of prediction of probable outcomes (ecological and economic) of any agricultural production system at any location is traced through an evolutionary path of trial and error, transfer by analogy, correlation/regression, analysis of variance, multivariate analysis, and systems analysis. These methods all remain in use and are not mutually exclusive. The implications of each method for climate impact assessment are discussed, and examples of relevant research are offered. The focus is on impacts of climate on agricultural production, with impacts on the food system more generally receiving less emphasis.

5.2 AGROCLIMATIC ANALYSIS: RETROSPECT

5.2.1 Trial and Error

The whole foundation of present food and fiber production rests upon thousands of years of farmer trial and error through hundreds of human generations. Coupled with keen observations of climate/weather/crop/livestock interactions, farmer trial and error has produced most of our domesticated plants and animals, as well as many stable and productive agricultural systems. But the time-scale is daunting and the social cost incalculable, since for each incremental improvement there have been countless failures. Major objectives of agricultural research are to shorten the long time trajectory and reduce the social cost for the discovery and substitution of superior strategies and technologies.

Traditional crop and livestock technologies have evolved such that climate and weather information becomes an integral component of the total system. The often complex timing required to fit operations into the seasonal cycle and to avoid specific weather hazards is codified in ritual and custom. An excellent example is provided by Stanhill (1977), who shows a close correspondence between the timing and sequence of special prayers for rain in the Jewish liturgical calendar, established some 200 years ago, and the present-day dependence of wheat yields in Israel on the critical early part of the growing season. Careful analysis of such ritual and custom can yield valuable information about climatic patterns and weather hazards in regions where instrumental data are lacking. Jodha and Mascarenhas (this volume, Chapter 17) report a variety of traditional indicators of and adjustments to climate variation.

The primary objective of most traditional systems is to minimize year-to-year variation in productivity and, especially, to minimize the risk of total loss of crop and/or livestock. But this stability exacts a price in terms of potential yields foregone. While the traditional-crop cultivars and livestock breeds are hardy and resilient to the impact of climatic variation and weather hazard, they are usually low-yielding and incapable of an economic response to added inputs or new management techniques. So well adapted and finely turned are some of these systems that sudden change in any major component—cultural, biological or physical—can cause massive disruption (see Le Houérou, this volume, Chapter 7). The lesson here is that a thorough understanding of climate/weather/crop/livestock interactions in the existing system is necessary before new or `improved' technologies can be introduced.

Modern, high-technology agricultural systems usually aim at maximizing the expectation of profit or yield, using crop cultivars and livestock breeds that have been produced to fit specific environments and markets, and inputs of fertilizers, herbicides, pesticides and machine energy. Normally, buffering reserves of food and/or capital permit such systems to adopt higher-risk strategies that lead to much greater production on a time-averaged basis. Acceptance of an occasional crop loss or uneconomic yield may be normal for a capital-intensive farmer, but it is unlikely to be acceptable to a subsistence farmer. These distinctions are important when globally assessing climatic impact on agricultural production. Estimation of risk is an important component of agricultural analysis, but the level of risk acceptance must be taken into account.

What kind of climate impact studies correspond to the history of trial and error in the development of agriculture in its environmental context? Naturally, the studies are primarily cultural, like that of Stanhill mentioned earlier, and historical. An interesting example of historical study is that of Parry (1978), who has documented the location of cultivation limits in Scotland between 1600 and 1800, then traced the shifts of these limits as an expression of climatic (and other) factors. Chapter 14 of this volume describes the methods in detail. Such studies record the trials and errors of agricultural practices in the face of a changing climate or extreme events.

Experiencing a changed climate at a particular location may be analogous to experiencing a new climate at a different place. The movement of people into New World agricultural lands and the process of trial and error, whereby optimistic expectations of the settlers yielded to the realities of different climates, has been documented in North America by Kupperman (1982) for the eastern seabord, Malin (1944) for Kansas, and Hargreaves (1957) for the northern Great Plains. Similar studies can be found for Australia (Heathcote, 1965; Williams, 1974).

The mix of immigrants to new lands created possibilities for trial and error experiments. Malin (1944) cites the key role of German Mennonite farmers who migrated from southern Russia in the 1870s to Kansas, bringing drought and cold-resistant varieties of hard red winter wheat with them. Over time these experimental efforts became professional and led to systematic trials, the major research device of the agricultural experiment station. With such trials and related selection and breeding, hard red winter wheat was adjusted to climates both warmer and colder and wetter and drier than its Kansas source area (Rosenberg, 1982).

5.2.2 Transfer by Analogy

Evidence suggests that the earliest cultivators recognized that natural vegetation could provide an index of site quality for their crops. Modern man has added a little to this basic concept—the transfer of information by analogy. The basic hypothesis is that all occurrences of a defined class of land will respond similarly to any imposed treatment. Climate, soil, vegetation and multi-attribute land classifications exemplify this approach. These classifications then provide a basis for the selection of `representative' experimental sites and for the subsequent extrapolation of results to other sites that share similar properties. Most current agrobiological research rests firmly upon such a foundation. Impact assessment can also employ analogues as simulators of future climate change. Analogues are sought that have the characteristics of the simulated or predicted climate, and the crop types or natural vegetation found within such climatic locations serve as the simulated or predicted vegetation.

Such a strategy is logical when the understanding of functional relationships between site attributes and crop response is qualitative or lacking, since this understanding is not required for classification. However, the better such knowledge is, the better will be the choice of attributes and the resultant classification. The thematic maps produced (that is, soil, land, vegetation) form a major component of an information system that is relatively inexpensive and highly portable. Usually agricultural research strategy is based upon climate and/or soil classifications, while forestry and pastoral research may place additional emphasis on vegetation classification.

Major deficiencies of the analogue approach reside in the static, multi-attribute character of the classifications upon which it is based and the implicit assumptions of covariance of attributes within mapped units. Compounding this is the location, season, cultivar and management-specific nature of the results from traditional agronomic experiments. For the individual farmer, the ideal location for an experiment is on his or her farm or as close as possible, since successful extrapolation of results is observed to hinge on proximity to the experimental site. Accordingly, there is continuing sociopolitical pressure to extend the network of research stations and experimental sites.

Given that agricultural research strategy will remain firmly based upon concepts of transfer of information by analogy for some time to come, there is ample scope for improvement and refinement of climate, land and soil classifications and for optimization of experimental networks. Numerical taxonomic analysis and/or pattern analysis (Sneath and Sokal, 1974; Williams, 1976) provide an array of classifications. The more relevant the attributes are, the better is the chance of a useful result. Commonly, the attributes measured represent a compromise between sampling density and site measurement.

Agroclimatic and bioclimatic classifications provide illustrations of the basic problems inherent in the analogue approach. While there is a considerable literature on bioclimatic classification and associated technologies, most of the general, multipurpose classifications are of limited use in solving specific problems. More direct coupling of climate data and specific crop response data offers prospects of more relevant classifications.

Agroclimatological zonation has always been particularly attractive to data-poor developing countries without an extensive network of meteorological and agricultural stations. They construct broad agroclimatological or agroecological zones using available temperature, precipitation, and soil and crop data. One example that illustrates this approach is the work of Jaetzold (Jaetzold and Kutsch, 1982; Jaetzold and Schmidt, 1982–83), who was asked by the Kenyan Ministry of Agriculture to provide a highly differentiated system of agroecological zones to help decide which variety of crops would best utilize the natural potential of a given district of arable land (Jaetzold, 1983). The main zones are given in Table 5.1; the rows are based on annual mean temperature, differentiated where appropriate by maximum or minimum temperature and frost occurrence. The columns are derived from a water balance model that gives the yield probabilities of leading crops (in the cells) and roughly reflects the precipitation/evaporation ratio. This main zonation is further subdivided to give actual varietal suggestions by length of season, soil type, plant density, and the like, samples of which are given in Figure 5.1 and Table 5.2. In effect these varietal suggestions are predictions that these crops will fare well if planted under the given conditions of climate and soils, predictions derived from analogous plantings elsewhere under similar conditions.

Analogue methods are currently in use to predict potential agricultural change under conditions of climatic change, particularly CO_2-induced change. At a continental scale, a characteristic bioclimatic classification is that of Holdridge (1947), based on temperature, precipitation and evaporation. This classification currently is being used to analyze the impacts of a CO_2-induced climate change (Emanuel *et al.*, in press). At other scales of analyses in such data-rich countries as the United States, shifts in the boundaries of the corn belt have been projected for a hypothetical CO_2-induced climate change by Newman (1980) and Blasing and Solomon (1983). The studies on crop yields and climate change by the US National Defense University (1980, described by Glantz *et al.*, this volume, Chapter 22) are a final example of assessment by analogy, in this case drawing on the experience of a group of experts.

5.2.3 Correlation/Regression

Since the pioneering work of Hooker (1907) and, more particularly, Fisher (1924), both simple and multiple regression techniques have become standard practice in the agricultural and biological services, both for exploratory data analysis and for prediction. Such empirical/statistical modes of crop/weather analysis dominate the voluminous literature of agroclimatology. Correlations have been established among a wide range of environmental variables and virtually all aspects of crop production. The utility of many such correlations under the conditions in which they were developed is not doubted, but the majority have limited application. Generally, the simpler the measure used, for example, total annual or seasonal rainfall, or annual mean air temperature, the more location-specific is the relationship.

Data on crop yield, temperature, and precipitation for a given district are the central components in statistical regression models. As reported by Waggoner (1983), the model for a particular crop in a particular area is generally expressed as

$$Y_i=a+b_1t_i+b_2X_{2i}+ \dots +b_nX_{ni},$$

where

Y_i = estimated yield in the *i*th year;
a = intercept;
t_i = surrogate for technology in the *i*th year;
b_1 = coefficient representing the effect of technology in quintals/hectare/year;
b_2 to b_n = coefficients representing the effect in quintals/hectare/ unit change in the weather;
X_{2i} to X_{ni} = weather variables such as precipitation, temperature, potential evapotranspiration (PET), and evapotranspiration (ET) in the *i*th year.

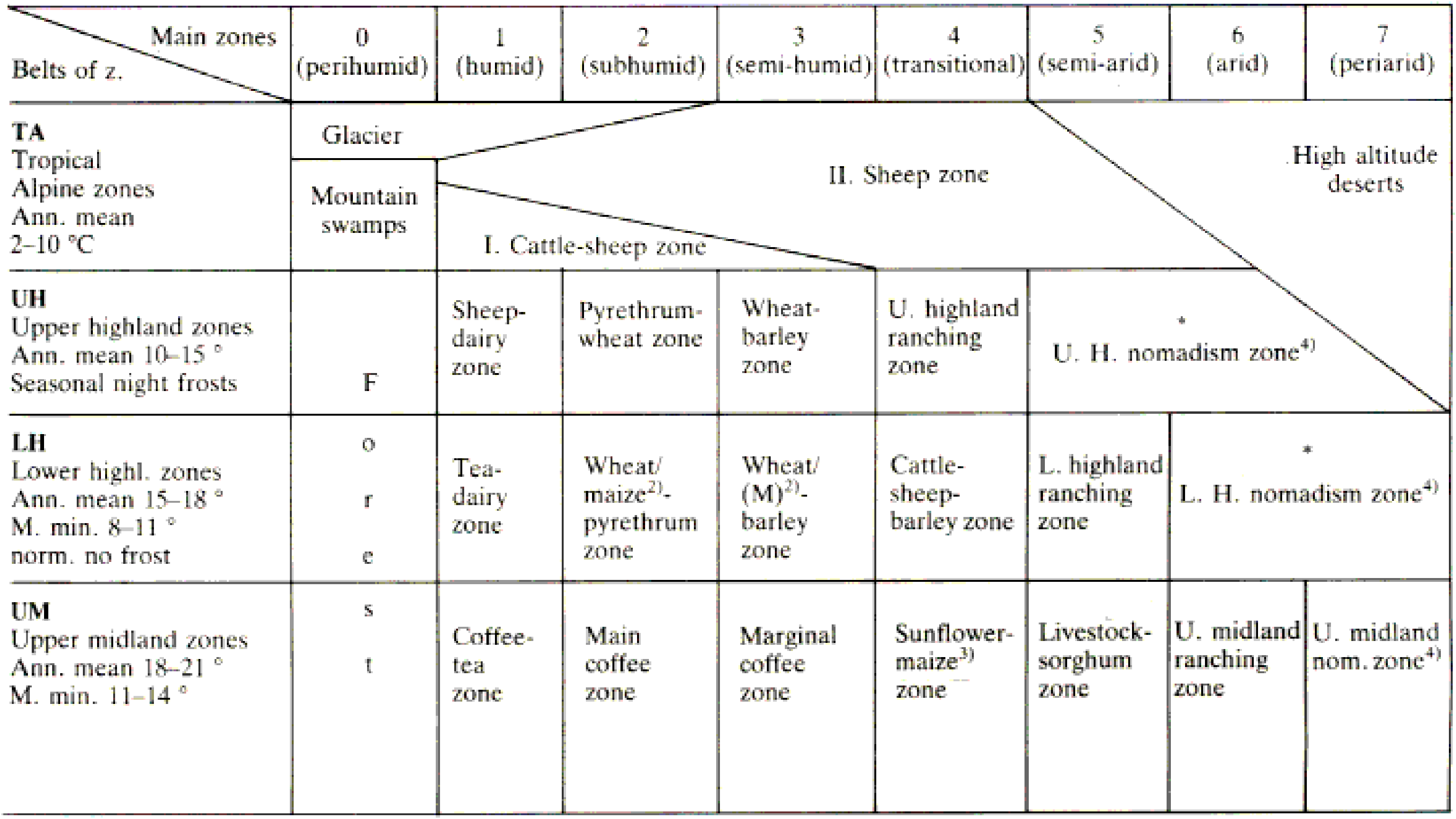
Thus, to quote Waggoner, `by multiple linear regression the effect of weather, factor by factor, on the yields of crops is distilled from a history of weather and yields, accumulated for decades by faithful observers'. Crop/climate regression models have been reviewed by Baier (1977) and Biswas (1980).

Greatest success with this approach has been achieved where one, or perhaps two, environmental factors dominate crop performance. Thus, in high latitudes, temperatures that determine length of growing season may be most critical; in midlatitude, subhumid to semi-arid regions, rainfall amount may be most critical; and in the humid tropics, with high rainfall and near-continuous cloud cover, solar radiation receipts may be most critical. The use of simple variables, such as monthly mean or seasonal mean precipitation and temperature, is common in large-area studies where the availability of data is restricted and/or computational limitations occur. Examples of successful applications of such analyses using simple data are provided by Thompson (1969a,b; 1970) in his analysis of weather and technology in the production of wheat, corn and soybeans in the United States.

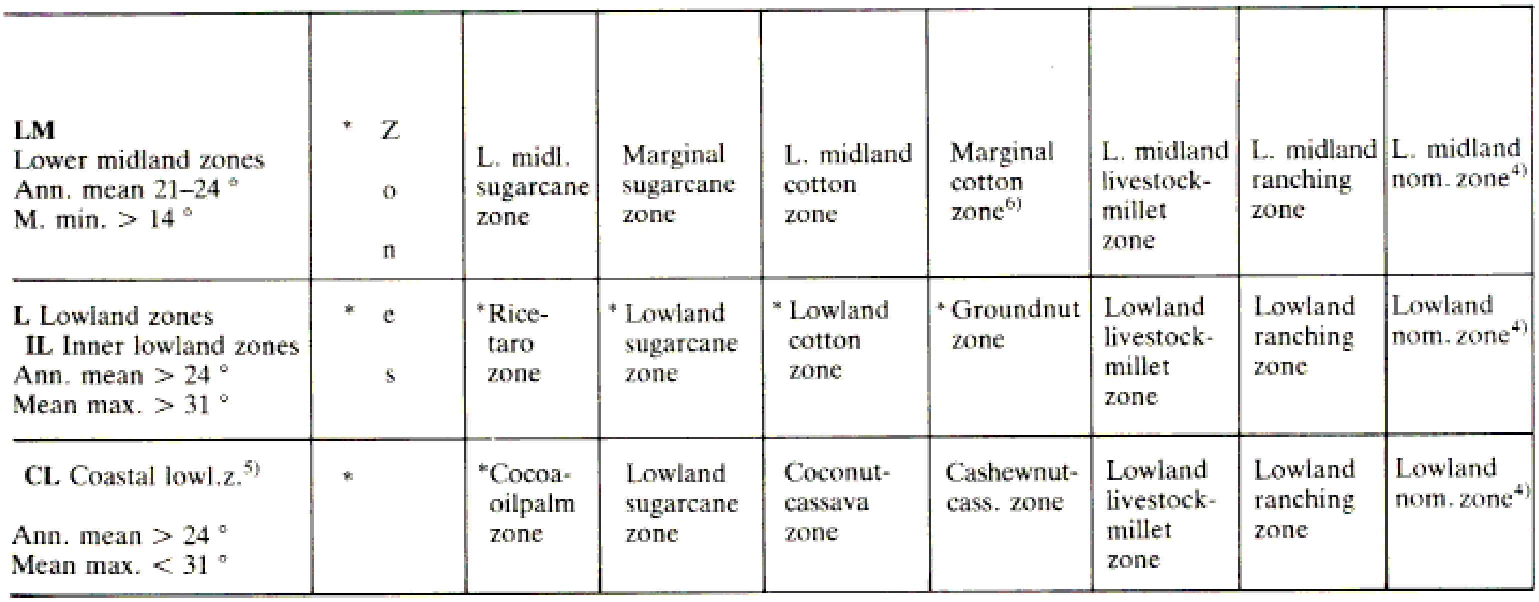
Usually, greater precision and generality are achieved if the primary climatic and/or soil data are transformed into indices that are more closely coupled to system performance. The derivation of crop/water stress indices from water-balance models (c.f. Baier and Robertson, 1968; Mack and Ferguson, 1968; Nix and Fitzpatrick, 1969) has proved successful in the explanation of large-area variation in wheat yields. Subsequent developments in the understanding of crop response to water stress have led to the formulation of empirical/statistical functions for a very wide range of crops (Doorenbos and Kassam, 1979).

Inherent problems of the empirical/statistical approaches based on regression-type analyses relate to explicit assumptions of linearity of response, the interdependence of so-called independent variables, implicit assumptions that correlation implies causation, and, inevitably, the location, season, cultivar and management-specific nature of resultant relationships. With care, these limitations can be minimized, and new techniques offer prospects of improved linear and nonlinear estimation procedures. Thus, Katz (1979), in a sensitivity analysis of statistical crop/weather models, demonstrated the potential value of ridge regression techniques as developed by Marquardt (1970) and Marquardt and Snee (1975).

Table 5.1 Agroecological zones of the tropics[1]. Reproduced with permission from Jaetzold (1983).



Main zones Belts of z.	0 (perihumid)	1 (humid)	2 (subhumid)	3 (semi-humid)	4 (transitional)	5 (semi-arid)	6 (arid)	7 (periarid)
TA Tropical Alpine zones Ann. mean 2–10 °C	Glacier Mountain swamps	II. Sheep zone I. Cattle-sheep zone					High altitude deserts	
UH Upper highland zones Ann. mean 10–15 ° Seasonal night frosts	Forest	Sheep-dairy zone	Pyrethrum-wheat zone	Wheat-barley zone	U. highland ranching zone	* U. H. nomadism zone[4]		
LH Lower highl. zones Ann. mean 15–18 ° M. min. 8–11 ° norm. no frost		Tea-dairy zone	Wheat/maize[2]-pyrethrum zone	Wheat/(M)[2]-barley zone	Cattle-sheep-barley zone	L. highland ranching zone	* L. H. nomadism zone[4]	
UM Upper midland zones Ann. mean 18–21 ° M. min. 11–14 °		Coffee-tea zone	Main coffee zone	Marginal coffee zone	Sunflower-maize[3] zone	Livestock-sorghum zone	U. midland ranching zone	U. midland nom. zone[4]



LM Lower midland zones Ann. mean 21–24 ° M. min. > 14 °	* Z o n	L. midl. sugarcane zone	Marginal sugarcane zone	L. midland cotton zone	Marginal cotton zone[6]	L. midland livestock-millet zone	L. midland ranching zone	L. midland nom. zone[4]
L Lowland zones **IL** Inner lowland zones Ann. mean > 24 ° Mean max. > 31 °	* e s	*Rice-taro zone	* Lowland sugarcane zone	* Lowland cotton zone	* Groundnut zone	Lowland livestock-millet zone	Lowland ranching zone	Lowland nom. zone[4]
CL Coastal lowl.z.[5] Ann. mean > 24 ° Mean max. < 31 °	*	*Cocoa-oilpalm zone	Lowland sugarcane zone	Coconut-cassava zone	Cashewnut-cass. zone	Lowland livestock-millet zone	Lowland ranching zone	Lowland nom. zone[4]

1. Inner Tropics, different zonation towards the margins. The T for Tropical is left out in the thermal belts of zones (except at TA), because it is only necessary if other climates occur in the same country. The names of potentially leading crops were used to indicate the zones. Of course these crops can also be grown in some other zones, but they are then normally less profitable.

2. Wheat or maize depending on farm scale, topography, a.o.

3. Maize is a good cash crop here, but maize also in LH 1, UM 1-3, LM and L 1-4;

4. Nomadism, semi-Nomadism and other forms of shifting grazing

5. An exception because of the vicinity of cold currents are the tropical cold Coastal Lowlands cCL in Peru and Namibia. Ann. mean there between 18 and 24 °C.

6. In unimodal rainfall areas growing periods may be already too short for cotton. Then the zone could be called Lower Midland Sunflower-Maize Zone.

* Not in Kenya

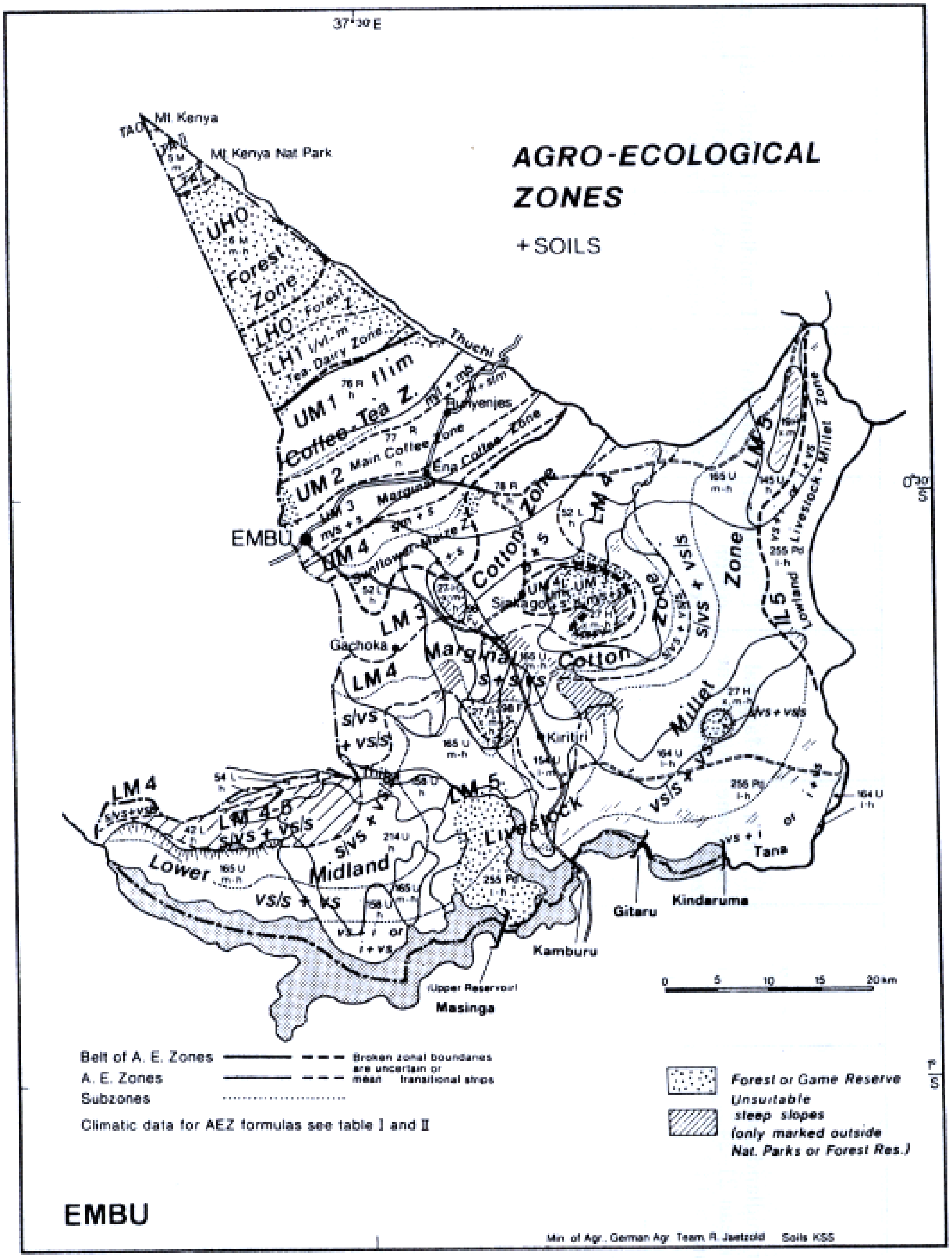


Figure 5.1 Agroecological zones, Embu District, Kenya. Reproduced with permission from Jaetzold (1983)

Table 5.2 Sample of a land use potential for an agroecological subzone. Reproduced with permission from Jaetzold (1983)

Embu District near the margins of rainfed cultivation.

LM 5= Lower Midland Livestock-Millet Zone

vs/s + vs with a very short to short and a very short cropping season

Good yield potential

1st rains, start norm. end of March: E. mat. foxtail millet like 1 Se 285 (~60%), e.

mat. proso millet like Serere 1; moth beans (~60%)
2nd rains, start norm. end of Oct.: E. mat. proso millet like Serere 1
Whole year: Buffalo gourds (light soils) and Marama beans, Jojoba (in valleys)

Fair yield potential
1st rains: Dwarf sorghum (50─60%), e. mat. bulrush millet (bird rejecting awned var.); bl. and green grams, cowpeas, chickpeas (on h. bl. soils, late pl.), v.e. mat. bambarra groundnuts (on light soils); dwarf sunflower
2nd rains: E. mat. foxtail millet like 1 Se 285, dwarf sorghum (50─60%); dwarf sunflower (40─50%); bl. and green grams, cowpeas, moth beans, chickpeas (on h. bl. soils, late planted)
Whole year: Sisal, castor C-15

Poor yield potential
1st and 2nd rains: Dryland comp. maize

Grassland and forage
> 3 ha/LU on mixed short grass savanna with buffel grass *(Cenchrus ciliaris)* and horsetail grass *(Chloris roxburghiana)* predominant; saltbush best palatable shrub for reestablishing pasture on overgrazed and eroded places.

Of course, regression techniques form part of the basic armory of methods used in the newer systems-based research strategies, both for exploratory data analysis and to quantify functional relationships between variables.

Studies employing regression have been developed for a variety of questions about agriculture in relation to climate variability and change. As in the studies of Thompson cited above, a major objective has been the identification of systematic patterns of yield variation. For example, Newman (1978) and Waggoner (1979) have examined whether there has been an increase or decrease in crop yield variability between the 1930s and the present and whether there is a correlation in behavior between major grain-producing regions. In general, they find relative variability has decreased somewhat, while variability expressed as absolute yield has increased. Michaels (1982a) has examined the same question related to new high-yielding (green revolution) varieties of wheat in Mexico and India, using as a control US winter wheat. Contrary to US trends, the Mexican and Indian wheats do display increased variability.

Regression-centered studies were extremely popular during the 1970s as nations and regions tried to assess their vulnerability to climatic variability. Good examples of national studies are found in McKay and Allsopp (1977) for Canada, National Research Council (1976) for the United States, and Takahashi and Yoshino (1978) for Japan and southeast Asia. For the World Climate Conference, Oguntoyinbo and Odingo (1979) explored relations among agriculture, climatic variability and various other causal factors in Africa, while Mattei (1979), McQuigg (1979), and Fukui (1979) prepared perspectives on the semi-arid regions, temperate regions and humid tropics, respectively. All report on regression and correlation analyses quite extensively.

A recent application of a regression approach to impacts of long-term climatic change is found in Waggoner (1983). Waggoner explored what the impacts of an annual average warming of 1 °C and decrease of 10 percent in rainfall might be on wheat, corn and soybean production in the US Middle West, under assumptions of no adjustment or adaptation. While such studies are obviously tentative, they may give a sense of the order of magnitude of prospective impacts. These empirical/statistical models, like those that relate crop yields to atmospheric pressure patterns (Steyaert *et al.*, 1978; Michaels, 1982b) may give sound results, providing that climate change does not induce atmospheric patterns that lie outside the range for which the yield regressions have been developed. This was recently illustrated by Santer (1984), using the work of Hanus (1978), whose models for winter wheat usually predict actual West German yields within 4 percent, except for the anomalous year 1976. In that year precipitation in the key month of June was a quarter to a half of the long-term average for most of West Germany, effectively outside the range from which the regressions were developed. Applying scenarios derived from two general circulation models of CO_2-induced change to the Hanus models evidenced similar problems, leading Santer to conclude that simple multiple linear regression appraisal may be basically unsuitable for making any credible assessment of the impacts of climatic change on crop yields (Santer, 1984).

5.2.4 Multivariate Techniques

These techniques represent a logical mathematical development of regression-based analysis in that they permit simultaneous analysis of sets of interacting variables; multivariate analysis, factor analysis, principal component analysis, and principal coordinate analysis are examples. While of principal value for data reduction and in exploratory data analysis, they can provide a basis for useful prediction and partial explanation. However, the derived principal component values, eigenvalues, or factor scores remain static representations of dynamic interactive processes, and their validity is strictly limited to the data domains used to develop them. While it is possible to determine the relative contributions of separate variables to the derived composite axes, it is often difficult to provide any physical explanation for their operation.

Sophisticated applications of multivariate approaches are found in the work of Monteith (1972, 1977a,b, 1978a,b). Monteith (1972) developed a simple model of crop growth for tropical crops, including climatic factors, and has modified it for application in other climatic zones. For example, Monteith (1977b) employed the model to estimate the ultimate limit set by climate on the productivity of British farms, defining efficiency of crop production in thermodynamic terms as the ratio of energy output (carbohydrate) to energy input (solar radiation). Temperature and water supply were found to be the main climatic constraints on efficiency. Over most of Britain, where radiation and thermal climates are uniform, Monteith found rainfall to be the main discriminant of yield between regions.

Another example of climate impact studies employing multivariate analysis is found in the discussion of Gifford (1979) and Monteith (1978b), who have debated maximum growth rates for crops like maize, sorghum, millet and sugarcane (the so-called C_4 crops), that grow well only in warm climates, and potatoes, sugar beets, rice, kale and cassava, growing either in warm or cool climates. Such studies come close to attempts at full simulation of plant behavior. The simulations, discussed below, are based more on hypothesized causal relations than on observed historical relationships, but the distinction is often blurred.

5.2.5 Systems Analysis

Very simply, systems analysis is concerned with the resolution of any complex system into a number of simpler components and the identification of important linkages between them. Subsequent synthesis in the form of a symbolic representation (diagrams, flow charts) that is formalized as a set of logical statements or algorithms and mathematical formulae (program) leads to the construction of a model of the real system. This model is then tested, using appropriate data inputs, and revised and developed to the point where it successfully simulates the behavior of the real system. Beyond this point the model can be used to predict probable outcomes of experiments performed on the system. For many complex systems simulation-based experiments represent the only possible means of examining perturbations to the system. Climate and weather systems and biological systems are examples of complex systems that can benefit from the systems approach. Figure 5.2 offers a generic representation of a plant-level simulation model combining the physics of the water balance with the physiology of the growing plant. Simulation models based on such process models have been used both in the United States and Europe to simulate the behavior of plants in response to a CO_2-induced climate change (personal communication, Sakamoto, 1984). The effects of a climate change potentially induced by CO_2 (+1 °C temperature/–10% precipitation) is shown for North Dakota spring wheat in Figure 5.3 from Waggoner (1983). The warmer and drier climate shifts the frequency of yields simulated from actual 1949–80 weather to yields two quintals lower, from a median of 8.5 to 6.5 quintals per hectare of yield. Using the simpler and more general Briggs plant biomass model for Europe, Santer (1984) has simulated two sets of general circulation model (GCM) climate results for a doubling and quadrupling of atmospheric carbon dioxide. He concludes that a simple crop/weather simulation model may be more suitable for the purposes of agricultural impact analysis than the linear regression models frequently used in such studies.

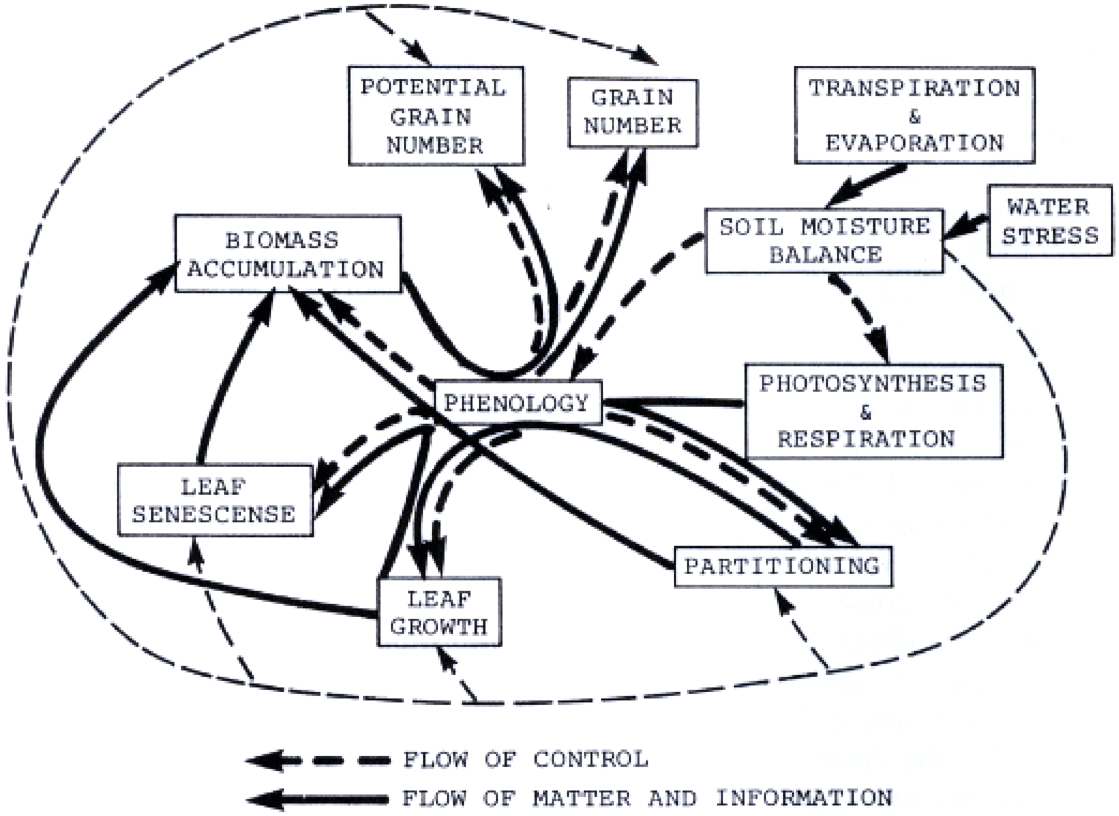


Figure 5.2 Plant process model diagram. Source: Hodges, T. (1984), personal communication

The process of formal analysis of any complex system yields other benefits in that it formalizes what is known about the system, identifies the more important components and processes and significant constraints on performance, and provides a suitable vehicle for testing alternative management strategies and the `what if ' questions posed by scenarios of global climatic change. Despite the proliferation of systems terminology and its ready incorporation into program titles and statements of research objectives, few agrobiological research strategies are truly systems-based. Essentially, this is because a systems-research strategy demands interdisciplinary teamwork that transgresses the boundaries of long-established discipline and subject-specialist groups and competes with them for scarce resources. As in any research team, leadership is critical, but special problems relate to the maintenance of subject-specialist skills of team members, peer recognition, and the allocation of rewards and responsibilities. Most successful systems-research groups have evolved around a nucleus of a small group of committed scientists rather than through the imposition of a systems-research structure by higher authority. Glantz *et al.* (Chapter 22, this volume) discuss the achievements and difficulties of several systems-oriented studies of climate impacts.

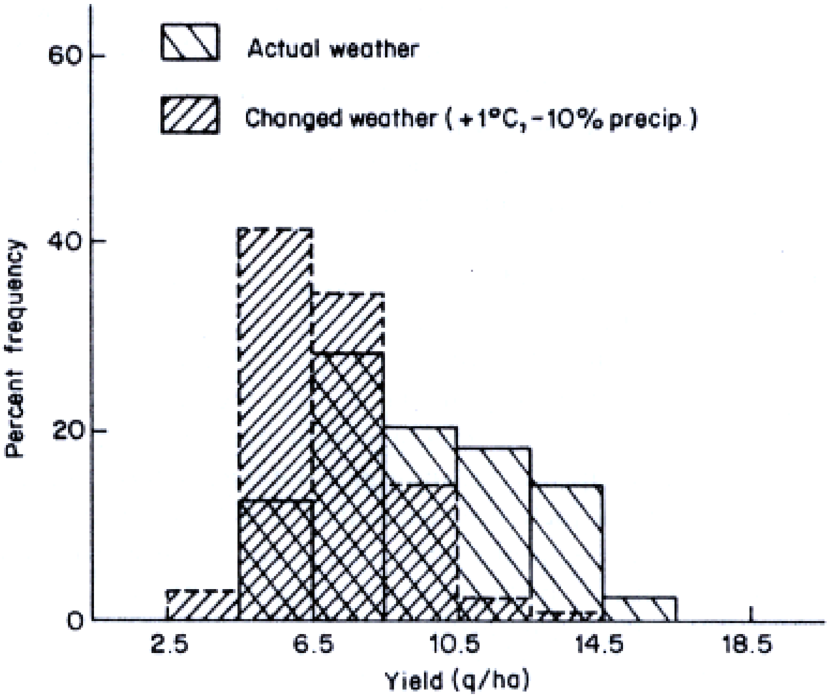


Figure 5.3 North Dakota simulated spring wheat yield (1949-80). Reproduced with permission from Waggoner (1983, 404)

5.3 AGROCLIMATIC SYNTHESIS: PROSPECT

Past, present and, predictably, future modes of agroclimatic analysis and synthesis are inextricably linked with the broader goals of agricultural, pastoral and forestry development and land and water resource management. What, then, are these goals? Obviously, these will vary from field to field, farm to farm, region to region, nation to nation and continent to continent. But an ecologically sound and socially responsible goal would be to develop technologies that lift production, while maintaining the long-term stability of the land and water resource base. Implementation of such technologies rests, ultimately, with the individual land manager, whether profit maximizer or subsistence farmer.

The central problem, then, is how to prescribe a technology that is relevant to the land, labor, capital and management resources of the individual land manager. If it were possible to predict the performance of any production system (crop, pasture/livestock, forest) at any location given a specified minimum set of soil/crop/weather-management data, then it would become possible to prescribe appropriate technologies. I have argued (Nix, 1968, 1976, 1981) that this ultimate objective is attainable, but that it requires a shift in emphasis away from reductionist/analytical research towards holistic/synthetic research. Of course, both types of research are necessary; they are complementary rather than competitive.

While much of current agrobiological research remains committed to the statistical differentiation of treatment effects on specific crops and cultivars, and on specific soils at specific locations in specific seasons, there are encouraging signs that greater efforts are being directed toward solution of the general problem. Of necessity, the earliest attempts at modeling agricultural systems were concerned with specific processes and/or specific products within restricted environments. Now, wide ranges of fully operational models of crop, livestock and forest systems are available or are under active development. Some, at least, are capable of general application across a spectrum of crops and environments. An example is `EPIC', the Erosion-Productivity Impact Calculator (Williams *et al.*, 1983a,b).

Active development of simulation modeling and access to sophisticated computer technology are not in themselves, however, sufficient evidence of adoption of a systems-research strategy that aims at prescriptive rather than descriptive solutions. If, as stated, the primary objective is to develop models capable of providing both general solutions and location-specific prescriptions, then the focus must be on the balanced development of two interactive components (a) the models, and (b) the data base. The models should be fully accessible and operational at all times, yet capable of continuing improvement in logical structure and function. The use of subsystem modules facilitates flexibility. The data base contains only those physical, biological, social and economic data that are specified as necessary for implementation of the model. Balanced development of both components is critical. Without access to prescribed input and test data, models cannot be implemented. On the other hand, the acquisition of data for which no specific requirement exists can be wasteful of scarce resources.

5.3.1 Model Development

Many would agree with Passioura (1973) that models should be simple; most would agree that they should be testable and capable of improvement after testing. Following the last two decades of development of models of ever-increasing complexity, there are signs of real efforts to return to simpler and more general crop models. In many cases, when it comes to implementation of the model in the real world, this is no more than a response to the reality of data limitations. In other cases the ability to simplify and generalize functional relationships has been a consequence of real improvements in understanding through basic research. Increasingly, models are being constructed using modular concepts that permit rapid updating and transfer of modules between models. Thus, it is possible to recognize common modules for, say, the water balances processes in many different models.

Van Dyne and Abramsky (1975) reviewed agricultural systems models then extant in some detail. They defined agricultural systems broadly and included those renewable natural resource systems and artificial biological resource systems that are directly under the control of man. They tabulated characteristics (structure; mathematical techniques; time-step; number of driving variables, processes and parameters; programming language; availability of flow charts and source code; stated objective and actual use and comments) for 90 papers and referenced 66 others in modeling applications to dairying and beef feedlotting, grazing sheep, irrigation, pest control, crop growth and yield, forestry, fisheries, wildlife management and agricultural economies. A general conclusion was that most models were poorly documented and thus not readily transferable (see also Robinson's discussion in Chapter 18). Many models provided a useful learning experience for the developers, but few become fully operational in day-to-day planning and management. It is hoped that this situation is changing, but Van Dyne and Abramsky's recommendations on documentation bear repeating:

1. specify objectives,
2. specify the hypotheses or assumptions used,
3. specify the general mathematical form of the model,
4. list the specific driving variables,
5. list the state variables used,
6. show a diagram of the model structure,
7. list equations or functional relationships,
8. list the computer code,
9. provide adequate comment statements,
10. report model deficiencies and limitations,
11. provide test samples of data used, and
12. provide output of a test case.

Although new scientific journals are catering to the specialized requirements of agricultural systems models, few can afford to publish lengthy computer program listings. Full documentation along the above lines as part of the program listing issued to potential users on microfiche could be one solution.

Various attempts have been made to classify the wide variety of models in use and under development, ranging from basic purpose (for example, descriptive *vs* prescriptive, simulation *vs* optimization) to type of formulation (for example, static *vs* dynamic, deterministic *vs* probabilistic). Van Dyne and Abramsky (1975) in their comprehensive review found that most agricultural system models were deterministic; the same would be true today. Stochasticity is introduced through the use of historical, synthesis or real-time weather and other environmental data. Ideally, the output should be expressed as a probability function.

Agricultural production systems of all kinds and at all scales draw upon three basic types of resources. Natural resources include the physical (for example, climate, terrain and soil) and the biological (for example, crop and livestock gene pools). Capital resources include items of plant and machinery, draught animals, fertilizers, herbicides, pesticides and so on. Human resources, the vital component, include all aspects of labor and management. Many models have concentrated on the biological and physical processes that determine crop growth, development and yield and/or animal production, and others have focused on optimization procedures that explore economic and/or social objectives. Few, as yet, have attempted to encompass the whole spectrum of interactions and relational processes. Robinson (Chapter 18, this volume) discusses modeling attempts to place the agricultural system in a global context.

An interesting systems perspective, though not formalized in a mathematical model, is that of Anderson (1979). Anderson, employing a general framework encompassing farm, regional, industrial, sectoral and national levels, has examined impacts of climate variations on Australian agriculture. Anderson begins with behavioral assumptions at the farm level, assuming first that satisfaction in farming depends on both personal characteristics and the probability distribution of financial performance. Financial performance depends in turn on allocative decisions, institutions and governmental interventions, prices and yields. The last two are, of course, in turn dependent on climate and a variety of other factors.

As Anderson (1979) reports, the effects of extreme climatic regimes have been sketched as unambiguously severe in affected regions. At high levels of geographic aggregation, impacts are often less severe because of the `cancelling out' of good and bad experiences (Waggoner, 1979). McIntyre (1973) estimated that gross rural output in Australia in the drought years 1965–66 and 1967–68 fell by 11 percent and 15 percent, respectively, below smoothed trend values. There is debate over the multiplier effects of drought on the national economy, some results suggesting amplification and others dampening.

The Erosion-Productivity Impact Calculator (EPIC) model referred to above is one of the most comprehensive agricultural system models now operational, and it is undergoing continued development. It addresses a vital socioeconomic and biophysical issue —soil erosion—at national levels, but it could have addressed climate change and variation equally well. EPIC has been developed by a large modeling team formed within the Agricultural Research Service of the United States Department of Agriculture. The brief given was to determine the relationship between erosion and productivity for the whole range of soil and crop interactions in the United States. Williams *et al.* (1983a) provide a detailed description of the model, which has physically based components for simulating erosion and plant growth and economic components for assessing the cost of erosion, determining optimal management strategies, and so on. The physical components include weather simulation, hydrology, erosion/sedimentation, nutrient cycling, plant growth, tillage and soil temperature.

5.3.2 Data Base Development

For every model it is necessary to identify the minimum data set necessary for its successful development, validation and subsequent implementation. The early stages of conceptualization, flow-charting, and programming usually rely on the current understanding of process, function and interaction as established by literature review. Any testing and validation relies on readily available data. Many modeling exercises never progress beyond this stage. Those that do soon realize that data limitations become the major constraint on further progress. This is particularly so when further development and testing require balanced and matching site/crop/weather-management data from a range of contrasting environments. Ideally, specific field, laboratory and/or controlled environment experiments would be designed to acquire the necessary minimum data set in the shortest possible time with the least expenditure. In reality, most model building and testing in this phase have had to rely on a fortuitous assembly of data from a range of sources. Few existing experiments, unfortunately, can satisfy even the barest minimum requirement for balanced and matching sets of soil/crop/weather-management data.

Proposals that standardized data sets be collected from experiments are not new. A number of national and international research programs have adopted this principle. What is new about the concept of *minimum* data sets is that it arises directly from the adoption of a systems-research strategy. Each model specifies the minimum data set necessary for its development, valid action and implementation. Review of existing operational models of agricultural production systems in general, and of crop systems in particular, indicates that many data items are common to all minimum data sets. In fact, a remarkable convergence in specification is under way. All share the need for primary weather data; terrain and soil attributes that modulate water balance and nutrient cycling; plant growth attributes that specify growth and development responses and yield accumulation processes; and management inputs that modify any of the foregoing. While it is possible to erect a hierarchy of minimum data sets with increasing range, precision, accuracy and frequency of measurement, at each level emphasis remains on a balanced monitoring of the whole crop system (Nix, 1979).

A new international program, International Benchmark Site Network for Agrotechnology Transfer (IBSNAT), was initiated by the US Agency for International Development in 1983 with the objective of developing a systems-based strategy for agrotechnology transfer. Through collaborative experiments in a large number of tropical and subtropical countries, standardized minimum data sets are to be collected for major food and cash crops. Development of operational models of these crops will proceed in parallel. The field experimenter will have access to models that will run on his or her own data, and the modelers will have access to standard minimum data sets from a wide range of contrasting environments. Useful and profitable interactions between the two groups can be expected to follow. Provided that the specific minimum data sets are monitored, no particular restrictions on experimental design need apply.

The IBSNAT program should help to remove constraints that currently hamper the further development and testing of operational models of crop systems. But what of the application of these developed models to real-world problems on an extensive scale? Such implementation requires that the appropriate model be coupled to a specified data base. Usually this will involve a climatic data file and either standardized or actual terrain, soil, crop and management variables. Obviously, the full flowering of these new technologies will depend on the coupling of an appropriate model to a resources data base that provides the necessary climate, terrain, soil and management data at the required scale and level of resolution.

New technologies currently available and under active development offer prospects of economical and efficient computer storage of geocoded data. Automatic digitizing equipment can process and store contour maps as arrays of grid points. Sophisticated surface fitting algorithms (see, for example, Wahba and Wendelberger, 1980) can be used to reconstruct the contoured surface, but more importantly, to estimate slope, aspect, elevation, position in landscape, water concentration, and overland flow trajectories and other important terrain-related attributes. Combined with similar algorithms that permit estimation of long-term mean climatic data at any point (Williams, 1969; Williams *et al.*, 1980; Hutchinson *et al.*, 1984), the stage is set for the derivation of necessary input data for models at levels of resolution that are useful.

The generation of stochastic sets of daily weather data based on statistical analysis of historical weather sequences and correlations between individual weather elements has been shown to be practicable. Initial attention focused on daily rainfall (see, for example, Nicks, 1974), but this has been extended to include other important elements such as maximum and minimum temperature and daily solar radiation (Richardson, 1981; Larsen and Pense, 1982). More recently still, Richardson (1984) has demonstrated that interpolation procedures can be used to generate satisfactory sequences of daily weather data at any geocoded point. The implications of this new technology for systems-based research and use of models in agrotechnology transfer are profound.

Technically, there are no reasons why these techniques should not be extended to generate stochastic sequences of daily weather data for much of the surface of the planet. On land, the value of such a data base for land evaluation, planning and management would be incalculable. Perturbation of the basic equations could be used to generate notional climates in some postulated climatic change and coupled to crop models to provide `what if ' answers to speculative questions.

5.4 CONCLUSION

All forms of crop/climate analysis have been used in land evaluation for specific forms of production; for analysis of crop/environment interactions in relation to crop adaptation; for crop monitoring and yield forecasting; for development and testing of new and modified management strategies and tactics; for risk assessment; for pest and disease assessment, management and control; for research and development strategy; and for developing our understanding of complex agricultural production systems.

Progress towards an ultimate goal of prediction of probable outcomes (physical, biological, ecological, economic) of any specified management treatment on any production system at any location has followed an evolutionary path from simple observation, trial and error, transfer by analogy, regression, multivariate techniques, analysis of variance through to systems analysis.

Over time each of the methods of modeling crop systems has accounted for more of the variance in crop yields (Nix, 1983). As shown in Figure 5.4, simple observation may be associated with 15 percent of the explained variance, trial and error field tests about 40 percent, transfer by analogy, 50 percent, and correlation and regression, 65 percent. The first generation (0) of systems and simulation explains about 80 percent of the variance, and future generations (1, 2, 3) of these models might bring it to 90 percent.

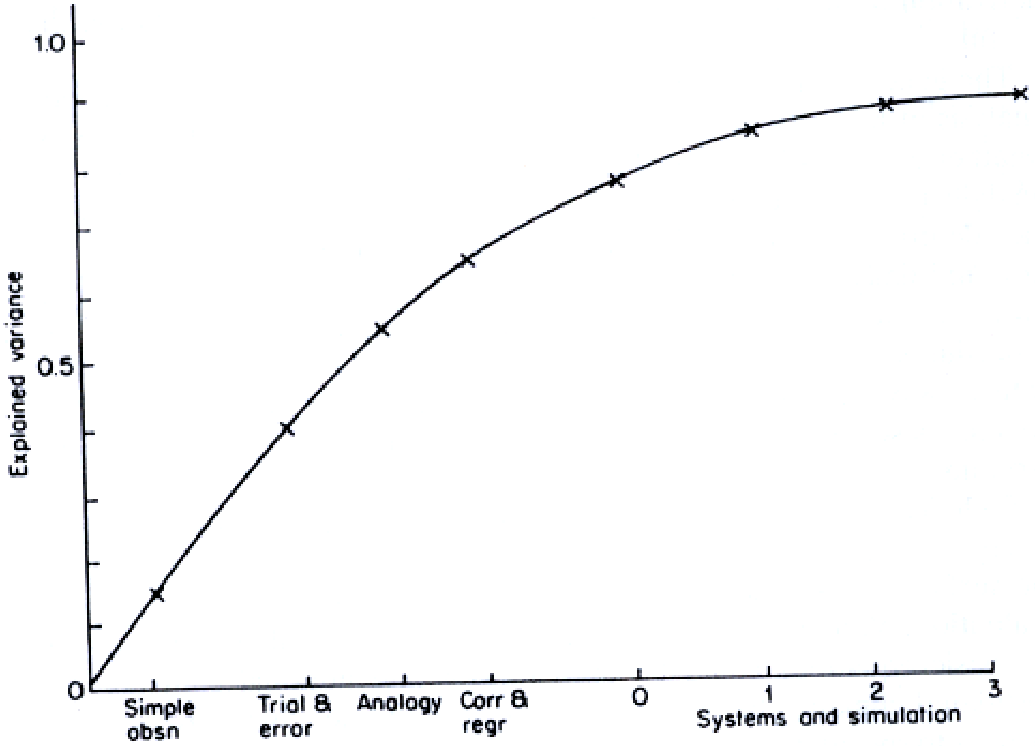


Figure 5.4 Modeling crop system. (Source: Sakamoto, 1983, modified after Nix, 1983)

It must be emphasized that these methods did not evolve in direct linear succession and are not mutually exclusive. Each can be expected to continue to play a role in climate impact assessment. Obviously, however, systems analysis and simulation techniques offer the best prospects of understanding and managing the complex interactions between climate and agricultural production systems.

In recent years the possibility of secular climatic change has focused attention on climate-related human activities and, in particular, agricultural production. While most scientists grapple with the problems of predicting crop response to weather variations within existing climate, a few have been so bold as to make predictions about global food production in relation to postulated climatic change. The empirical/statistical modes of analysis used generally do not inspire confidence in the results.

Agricultural production system models now operational and currently under development offer prospects of both general solutions and location-specific prescriptions. Their impact on all aspects of agricultural research, development and production will be profound. Because climate and weather provide primary inputs and forcing functions, these models offer the most direct means of climate impact assessment. General application of the new generation models, however, will depend on the availability of the minimum data sets that are specified as input. Accordingly, we can expect to see the development of dynamic interactive systems of environmental data banks coupled to appropriate simulation models that will be used for all aspects of agricultural development, planning and management.

REFERENCES

Anderson, J. R. (1979). Impacts of climatic variability on Australian agriculture. In *The Impact of Climate on Australian Society and Economy*. Commonwealth Scientific and Industrial Research Organization (CSIRO), P.O.B. 77, Mordialloc, Victoria, Australia.

Baier, W. (1977). *Crop-weather Models and Their Use in Yield Assessment.* WMO No. 458, Technical Note 151. World Meteorological Organization, Geneva: 48 pages.

Baier, W., and Robertson, G. W. (1968). The performance of soil moisture estimates as compared with the direct use of climatological data for estimating crop yields. *Agricultural Meteorology,* **5**, 16-31.

Biswas, A. K. (1980). Crop-climate models: A review of the state of the art. In Ausubel, J., and Biswas, A. K. (Eds.) *Climatic Constraints and Human Activities,* pp. 75-92. Pergamon Press, Oxford.

Blasing, T. J., and Solomon, A. M. (1983). *Response of the North American Corn Belt to Climate Warming.* Prepared for the US Dept. of Energy. National Technical Information Service, US Dept. of Commerce, Springfield, Virginia.

Doorenbos, J., and Kassam, A. H. (1979). *Yield Response to Water.* FAO Irrigation and Drainage Paper. Food and Agriculture Organization, Rome: 193 pages.

Emanuel, W. R., Shugart, H. H., and Stevenson, M. P. (in press). Climatic change and the broad-scale distribution of terrestrial ecosystems complexes. *Climatic Change* (accepted for publication May 1984).

Fisher, R. A. (1924). The influence of rainfall distribution on the yield of wheat at Rothamstead. *Royal Society of London Philosophical Transactions,* **Series B213**, 89-142.

Fukui, H. (1979). Climatic variability and agriculture in tropical moist regions. In *Proceedings of the World Climate Conference,* pp. 426-474. World Meteorological Organization, Geneva.

Gifford, R. M. (1979) *Australian Journal of Plant Physiology,* **1**, 107.

Hanus, H. (1978). *Forecasting of Crop Yields from Meteorological Data in the EC Countries.* Statistical Office of the European Communities, Agricultural Statistical Studies No. 21, Luxembourg.

Hargreaves, M. W. M. (1957). *Dry Farming in the Northern Great Plains 1900-1925.* Harvard University Press, Cambridge, Massachusetts.

Heathcote, R. L. (1965). *Back of Bourke.* Melbourne University Press, Carlton, Victoria, Australia.

Holdridge, L. R. (1947). Determination of world plant formations from simple climatic data. *Science,* **105**, 367-368.

Hooker, N. H. (1907). Correlation of weather and crops. *Royal Statistical Society Journal,* **70**, 1-42.

Hutchinson, M. F., Booth, T. H., McMahon, J. P., and Nix, H. A. (1984). Estimating monthly mean values of daily total solar radiation for Australia. *Solar Energy* (in press).

Jaetzold, R. (1983). Agro-ecological zonation in Kenya. *Network for Environment & Development,* **3**, (3, December), 1-4. Available from International Development Program, Center for Technology, Environment, and Development, Clark University, Worcester, Massachusetts.

Jaetzold, R., and Kutsch, H. (1982). Agro-ecological zones of the tropics, with a sample from Kenya. *Der Tropenlandwirt,* **83**, (2, April), 15-34.

Jaetzold, R., and Schmidt, H. (Eds.) (1982-83). *Farm Management Handbook of Kenya.* Volume 2: *Natural Conditions and Farm Management Information.* Part A: West Kenya (1982), Part B: Central Kenya (1983), Part C: East Kenya (1983). Ministry of Agriculture, Nairobi.

Katz, R. W. (1979). Sensitivity analysis of statistical crop-weather models. *Agricultural Meteorology,* **20**, 291-300.

Kupperman, K. O. (1982). The puzzle of the American climate in the early colonial period. *The American Historical Review,* **87** (5, December), 1262-1289.

Larsen, G. A., and Pense, R. B. (1982). Stochastic simulation of daily climatic data for agronomic models. *Agronomy Journal,* **74**, 510-514.

Mack, A. R., and Ferguson, W. S. (1968). A moisture stress index for wheat by means of a modulated soil moisture budget. *Canadian Journal of Plant Science,* **48**, 535-543.

Malin, J. C. (1944). *Winter Wheat in the Golden Belt of Kansas: A Study in Adaptation to Subhumid Geographical Environment.* University of Kansas Press, Lawrence, Kansas.

Marquardt, D. W. (1970). Generalised inverses, ridge regression, biased linear estimation and nonlinear estimation. *Technometrics,* **12**, 591-612.

Marquardt, D. W., and Snee, R. D. (1975). Ridge regression in practice. *The American Statistician,* **29**, 3-20.

Mattei, F. (1979). Climatic variability in agriculture in the semi-arid tropics. In *Proceedings of the World Climate Conference,* pp. 475-509. World Meteorological Organization, Geneva.

McIntyre, A. J. (1973). Effects of drought in the economy. In Lovett, J. V. (Ed.) *The Environmental, Economic and Social Significance of Drought.* Angus and Robertson,Sydney.

McKay, G. A., and Allsopp, T. (1977). Climate and climate variability. In *Climatic Variability in Relation to Agricultural Productivity and Practices.* Committe on Agrometeorology, Department of Agriculture Research Branch, Ottawa, Canada.

McQuigg, J. D. (1979). Climatic variability and agriculture in the temperate regions. In *Proceedings of the World Climate Conference,* pp. 406-425. World Meteorological Organization, Geneva.

Michaels, P. J. (1982a). The response of the `green revolution' to climatic variability. *Climatic Change,* **4**(3), 255-271.

Michaels, P. J. (1982b). Atmospheric pressure patterns,, climatic change and winter wheat yields in North America. *Geoforum,* **13**(2), 263-273.

Monteith, J. L. (1972). Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology,* **9**, 747-766.

Monteith, J. L. (1977a). Climate. In De T. Alvim, P. (Ed.) *Ecophysiology of Tropical Crops.* Academic Press, New York and London.

Monteith, J. L. (1977b). Climate and the efficiency of crop production in Britain. *Royal Society of London Philosophical Transactions,* Series **B281**, 277-294.

Monteith, J. L. (1978a). Models and measurement in crop climatology. *International Society of Soil Science, Canada,* 385-398.

Monteith, J. L. (1978b). Reassessment of maximum growth rates for C_3 and C_4 crops. *Exploratory Agriculture,* **14**, 1-5.

National Research Council (1976). *Climate and Food: Climate Fluctuation and US Agricultural Production.* Committee on Climate and Weather Fluctuations and Agricultural Production, National Academy of Sciences, Washington, DC.

Newman, J. E. (1978). Drought impacts on American agricultural productivity. In Rosenberg, H. J. (Ed.) *North American Droughts.* Westview Press, Boulder, Colorado.

Newman, J. E. (1980). Climate change impacts on the growing season of the North America `cornbelt'. *Biometeorology,* **7**(2), 128-142.

Nicks, A. D. (1974). Stochastic generation of the occurrence, pattern and location of maximum amounts of daily rainfall. In *Proceedings of Symposium on Statistical Hydrology, Tucson, Arizona,* pp. 154-171 (Miscellaneous Publication No. 1275).

Nix, H. A. (1968). The assessment of biological productivity. In Stewart, G. A. (Ed.) *Land Evaluation.* Macmillan, Melbourne, Australia.

Nix, H. A. (1976). Climate and crop productivity in Australia. In *Rice and Climate.* IRRI, Los Banos, Philippines.

Nix, H. A. (1979). Agroclimatic analogues in transfer of technology. In *Development and Transfer of Technology for Rainfed Agriculture, Proceedings of an International Symposium, Hyderabad, India.* ICRISAT, Hyderabad.

Nix, H. A. (1980). Strategies for crop research. *Proceedings of the Agronomic Society of New Zealand,* **10**, 107-110.

Nix, H. A. (1981). Simplified simulation models based on specified minimum data sets: The CROPEVAL concept. In Berg, A. (Ed.) *Application of Remote Sensing to Agricultural Production Forecasting.* Balkema, Rotterdam.

Nix, H. A. (1983). Minimum data sets for agrotechnology transfer. Presented at the *ICRISAT-IBSNAT-SMSS International Conference on Minimum Data Sets for Agrotechnology Transfer, Hyderabad, India, March 1983.* Conference Proceedings published by IBSNAT, Honolulu (forthcoming 1984).

Nix, H. A., and Fitzpatrick, E. A. (1969). An index of crop water stress related to wheat and grain sorghum yields. *Agricultural Meteorology,* **6**, 321-337.

Oguntoyinbo, J. S., and Odingo, R. S. (1979). Climatic variability and land use. In *Proceedings of the World Climate Conference,* pp. 552-580. World Meteorological Organization, Geneva.

Parry, M. L. (1978). *Climatic Change, Agriculture and Settlement.* William Dawson & Sons, Folkestone, UK.

Passioura, J. P. (1973). Sense and nonsense in crop simulation. *Journal* of *the Australian Institute of Agricultural Science,* **39**, 181-183.

Richardson, C. W. (1984). Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resources Research,* **17**(1),182-190.

Richardson, C. W. (1984). *WGEN: A Model for Generating Daily Weather Variables.* USDA, ARS-8. US Dept. of Agriculture, Agricultural Research Service, Washington, DC: 83 pages (forthcoming 1984).

Rosenberg, N. J. (1982). The increasing CO_2 concentration in the atmosphere and its implications on agricultural productivity II. Effects through CO_2^-induced climatic change. *Climatic Change,* **4** (3), 239-254.

Sakamoto, C. M. (1983). New generation of crop models. Lecture presented at the *Agroclimatic Technology Program for Southeast Asia, April 11-15, 1983, Bangkok, Thailand.*

Santer, B. (1984). Impacts on the agricultural sector. In Meinl, H., and Bach, W., Socioeconomic Impacts of Climatic Changes Due to a Doubling of Atmospheric CO_2 Content. Contract No. CL1-063-D, Commission of the European Communities, Brussels.

Sneath, P. H. A., and R. R. Sokal (1974). *Numerical Taxonomy.* W. H. Freeman and Co., San Francisco, California.

Stanhill, G. (1977). Quantifying weather-crop relations. In Landsberg, J. J., and Cutting, C. V. (Eds.) *Environmental Effects on Crop Physiology.* Academic Press, New York.

Steyaert, L. T., Leduc, S. K., and McQuigg, J. D. (1978). Atmospheric pressure and wheat yield modeling. *Agricultural Meteorology*, **19**, 23-24.

Takahashi, K., and Yoshino, M. M. (Eds.) (1978). *Climatic Change and Food Production.* University of Tokyo Press, Tokyo.

Thompson, M. L. (1969a). Weather and technology in the production of wheat in the United States. *Journal of Soil and Water Conservation*, **24**, 219-224.

Thompson, L. M. (1969b). Weather and technology in the production of corn in the US corn belt. *Agronomy Journal*, **61**, 453-456.

Thompson, L. M. (1970). Weather and technology in the production of soybeans in the central United States. *Agronomy Journal*, **62**, 232-236.

Van Dyne, G. M., and Abramsky, Z. (1975). Agricultural systems models and modelling: An overview. In Dalton, G. E. (Ed.) *Study of Agricultural Systems.* Applied Science Publishers, London.

Waggoner, P. E. (1979). Variability of annual wheat yields since 1909 and among nations. *Journal of Agricultural Meteorology*, **20**, 42.

Waggoner, P. E. (1983). Agriculture and a climate changed by more carbon dioxide. In National Research Council, *Changing Climate: Report of the Carbon Dioxide Assessment Committee*, pp. 383-418. National Academy Press, Washington, DC.

Wahba, G., and Wendelberger, J. (1980). Some new mathematical methods for variational objective analysis using splines and cross validation. *Monthly Weather Review*, **108**, 1122-1143.

Williams, G. D. V. (1969). Applying estimated temperature normals to the zonation of the Canadian Great Plains for wheat. *Canadian Journal of Soil Science*, **49**, 263-276.

Williams, G. D. V., McKenzie, J. S., and Sheppard, M. I. (1980). Mesolscale agroclimatic resource mapping by computer, an example for the Peace River region of Canada. *Agricultural Meteorology*, **21**, 93-109.

Williams, J. R., Dyke, P. T., and Jones, C. A. (1983a). EPIC: A model for assessing the effects of erosion on soil productivity. In *Proceedings of the Third International Conference on the State-of-the-Art in Ecological Modelling.*

Williams, J. R., Renard, K. G., and Dyke, P. T. (1983b). EPIC: A new method for assessing erosion's effect on soil productivity. *Journal of Soil and Water Conservation*, **38** (5), 381-383.

Williams, M. (1974). *The Making of the South Australian Landscape.* Academic Press, London.

Williams, W. T. (Ed.) (1976). *Pattern Analysis in Agricultural Science.* Elsevier/ CSIRO, New York.

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